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Dijet Mass Spectrum Limits on Flavor-Universal Colorons

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Abstract

Using recent $D\bar{O}$ data on the dijet mass spectrum, we present a limit on flavor-universal colorons. At 95% CL we find $M_c/\cot\theta > 837$ GeV. We discuss the implications of this limit for models of quark compositeness, non-standard gluon interactions, and dynamical electroweak symmetry breaking. In addition, we place a lower bound $\Lambda_{A8} > 2.1$ TeV on the scale of color-octet axial-vector contact interactions among quarks which could arise in models of quark compositeness.

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1 Introduction

The flavor-universal coloron model [1] was originally proposed to explain the apparent excess of high- E_T jets in the inclusive jet spectrum measured at the Fermilab Tevatron by the CDF Collaboration [2]. This model is a flavor-universal variant of the coloron model of Hill and Parke [3] which involves a minimal extension of the standard description of the strong interactions, including the addition of one gauge interaction and a scalar multiplet, but no new fermions. The flavor-universal coloron model of the strong interactions can be grafted onto the standard one-Higgs-doublet model of electroweak physics, yielding a simple, complete, and renormalizable theory. Alternatively, it can provide the basis for dynamical generation of electroweak symmetry breaking and the generation of the top quark's mass in models [4, 5] akin to top-color-assisted technicolor [6].

Previous work on the phenomenology of the colorons has considered effects on the ρ parameter [1, 4], the inclusive jet spectrum [1], the dijet spectrum and angular distributions [7, 8, 9], and b-tagged dijets [8]. The most recent of these analyses [9] put a limit $M_c/\cot\theta > 759$ GeV on the coefficient of the four-fermion contact interaction to which heavy coloron exchange would give rise.

This letter explores the effects colorons would have on the dijet mass spectrum measured at the Tevatron by the DØ Collaboration [10] and establishes a still stronger limit on contact interactions arising from colorons: $M_c/\cot\theta > 837$ GeV at 95% CL. In Section 2, we briefly review the model. Section 3 explains how our limit was derived. Section 4 discusses our conclusions and the implications for models of quark compositeness, non-standard gluon interactions, and dynamical electroweak symmetry breaking. We also present a separate limit on the scale of color-octet axial-vector contact interactions among quarks.

2 The model

In the flavor-universal coloron model [1], the strong gauge group is extended to $SU(3)_1 \times SU(3)_2$. The gauge couplings are, respectively, ξ_1 and ξ_2 with $\xi_1 \ll \xi_2$. Each quark transforms as a $(1,3)$ under this extended strong gauge group.

The model also includes a scalar boson Φ transforming as a $(3, \bar{3})$ under the two $SU(3)$ groups. For a range of couplings in the scalar potential, Φ develops a vacuum expectation value $\langle\Phi\rangle = \text{diag}(f, f, f)$ which breaks the two strong groups to their diagonal subgroup [1]. We identify this unbroken subgroup with QCD.

When the extended color symmetry breaks, the original gauge bosons mix to form an octet of massless gluons and an octet of massive colorons. The gluons interact with quarks through a conventional QCD coupling with strength g_3 . The

colorons ($C^{\mu a}$) interact with quarks through a new QCD-like coupling

$$\mathcal{L} = -g_3 \cot \theta J_\mu^a C^{\mu a} \quad , \quad (2.1)$$

where J_μ^a is the color current

$$\sum_f \bar{q}_f \gamma_\mu \frac{\lambda^a}{2} q_f \quad . \quad (2.2)$$

and $\cot \theta = \xi_2/\xi_1 > 1$. The mass of the colorons may be written

$$M_C = \left(\frac{g_3}{\sin \theta \cos \theta} \right) f \quad (2.3)$$

in terms of the parameters of the model.

Below the scale M_C , coloron-exchange may be approximated by the effective four-fermion interaction

$$\mathcal{L}_{eff} = -\frac{g_3^2 \cot^2 \theta}{2! M_C^2} J_\mu^a J^{\mu a} \quad . \quad (2.4)$$

This can be re-written in the form commonly used in studies of quark compositeness [11]

$$\mathcal{L}_{eff} = -\frac{4\pi}{2! \Lambda_{V8}^2} J_\mu^a J^{\mu a} \quad . \quad (2.5)$$

where the scale Λ_{V8} is defined by $\Lambda_{V8} \sqrt{\alpha_s} = M_C / \cot \theta$. Contact interactions of this kind tend to increase quark-quark scattering at high invariant mass above the standard QCD prediction.

3 Effects on the Dijet Spectrum

The DØ Collaboration recently [10] measured the inclusive dijet mass spectrum at $\sqrt{s} = 1.8$ TeV for dijet masses above 200 GeV and jet pseudorapidity $|\eta_{jet}| < 1.0$. The collaboration also measured the ratio of spectra at $|\eta_{jet}| < 0.5$ and $0.5 < |\eta_{jet}| < 1.0$ and used this to place a limit on certain models of quark compositeness. We use this same ratio of spectra to place limits on the effects of flavor-universal colorons.

We calculated the leading-order (LO) dijet spectrum

$$\begin{aligned} \kappa &\equiv \frac{d^3 \sigma}{dM d\eta_1 d\eta_2} (AB \rightarrow 2 \text{ jets}) \\ &= \sum_{abcd} \frac{x_a x_b M}{2 \cosh^2 \eta_{cm}} [f_{a/A}(x_a) f_{b/B}(x_b) + (A \leftrightarrow B, a \neq b)] \frac{d\sigma}{d\hat{t}} (ab \rightarrow cd) \end{aligned} \quad (3.1)$$

in terms of the jets' pseudorapidities (η_1, η_2 ; $\eta_{cm} \equiv 0.5(\eta_1 - \eta_2)$), combined invariant mass (M) and momentum fractions (x_a, x_b); the parton distribution functions ($f_{a/A}, f_{b/B}$); and the two-body parton scattering cross section

$$\frac{d\sigma}{d\hat{t}}(ab \rightarrow cd) = \frac{\pi\alpha_s^2}{\hat{s}^2}\Sigma(ab \rightarrow cd). \quad (3.2)$$

The leading QCD contributions to $\Sigma(ab \rightarrow cd)$ may be found in [12] and the contributions from heavy coloron exchange are given¹ in [1]. Note that we included only production of gluons and light quarks in our calculations since produced top quarks would not contribute appreciably to the DØ dijet sample²

Taking a series of different values for the coloron interaction strength $M_c/\cot\theta$, we then determined the ratio $\kappa(|\eta_{jet}| < 0.5)/\kappa(0.5 < |\eta_{jet}| < 1.0)$ at values of M corresponding to the weighted center of each mass bin³ measured by DØ in ref.[10]. We evaluated the fractional difference between the dijet spectra for pure QCD and for the various values of $M_c/\cot\theta$. To simulate a next-to-leading order (NLO) prediction of the effects of colorons, we multiplied a NLO QCD prediction obtained using the JETRAD program [14] by the LO fractional differences. The results are illustrated in Figure 1.

We extract a limit on the coloron interaction strength from the DØ data [10] using Bayesian techniques with a Gaussian likelihood function

$$P(x) = \frac{1}{\det S 2\pi^2} \exp\left(-\frac{1}{2}[d - f(x)]^T S^{-1}[d - f(x)]\right) \quad (3.3)$$

where d is the vector of data points for the different mass bins, $f(x)$ is the vector of theory points for the different masses at different values of $x \equiv 1/\Lambda^n$, and S is the covariance matrix. Motivated by the form of L_{eff} (eqn. (2.5)), the prior probability is assumed to be flat when $x = 1/\Lambda^2$. Since the ratio of spectra at NLO is sensitive to the choice of μ and parton distribution function, each possible choice is treated as a different theory. The 95% confidence limit (CL) on Λ is calculated by requiring that

$$Q(x) = \int_0^x P(x)dx = 0.95 Q(\infty) \quad (3.4)$$

The limit in x is then transformed back into a limit on Λ and thence into a limit on $M_c/\cot\theta$.

¹In ref. [1], the colorons' contributions are the terms in equations (4.2-4.5) in that paper which depend on coefficient c_1 .

²The number of top quarks produced is relatively small and a decaying top quark does not generally resemble a single high- E_T jet.

³As a check, we re-calculated the ratio for the very wide highest mass bin by integrating over M for $800 \text{ GeV} < M < 1400 \text{ GeV}$; this yielded the same ratio as keeping M fixed at the weighted center value of 873.2 GeV.

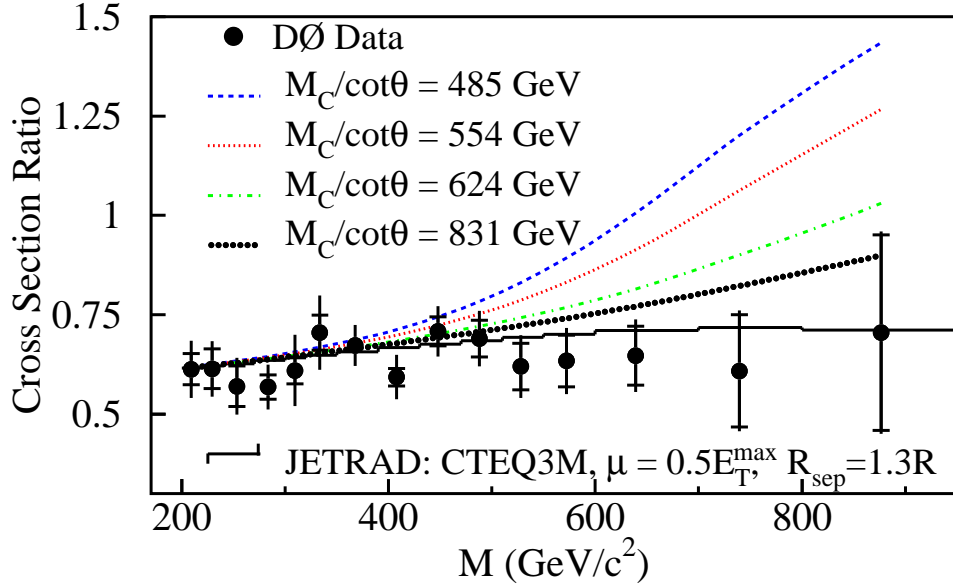


Figure 1: The ratio of cross sections, $\kappa(|\eta_{jet}| < 0.5)/\kappa(0.5 < |\eta_{jet}| < 1.0)$, as measured by DØ [10] compared to theory for different values of $M_c/\cot\theta$ (see text for details on how the coloron distributions are calculated). The error bars show the statistical and systematic uncertainties of the data added in quadrature, and the crossbar shows the size of the statistical error.

The most conservative lower bound we obtain at the 95% CL is $M_c/\cot\theta > 837$ GeV for the CTEQ3M pdf and $\mu = E_T^{\max}$ (where E_T^{\max} is the maximum jet E_T in the event) as illustrated in Figure 2. This limit is incompatible with the suggestion of a coloron interaction strength of order 700 GeV [1] in earlier measurements of the high E_T jet inclusive cross-section [2].

4 Discussion

Our limit places a new exclusion bound in the M_c vs. $\cot\theta$ parameter space of the flavor-universal coloron model. As shown in Figure 3, this improves on the recent DØ limit based on the dijet angular distribution [9]. Note that the region at $\cot\theta \approx 1$ where our limit appears to provide a direct lower bound on M_c has already been excluded by CDF’s search for new particles decaying to dijets [16]. This is fortunate, because our limit actually becomes less reliable here: the condition $M_c > \sqrt{\hat{s}}$, under which (2.4) is a reasonable approximation to coloron exchange, would no longer hold for the highest-energy data point. An updated search for new resonances decaying to dijets would be a useful complement to the bounds we report here.

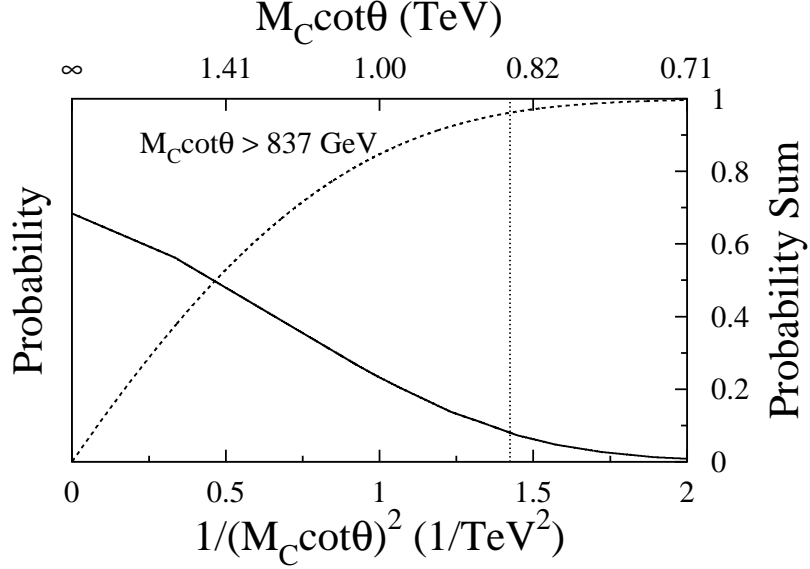


Figure 2: The probability distribution (solid curve) $Q(x)/Q(\infty)$ for the theoretical (JETRAD) prediction with $\mu = 1.0 \times E_T^{\max}$. The dashed curve shows the integral of the probability distribution and the dotted line shows the 95% CL on $M_c/\cot\theta$, i.e., 837 GeV.

In the context of the dynamical electroweak symmetry breaking model of [4] in which flavor-universal colorons help produce the mass of the top quark, the value of $\cot\theta$ is approximately 4. In other words, the interaction strength is near its upper limit for the Higgs phase of the model [1, 8]. Our bound implies that $M_c > 3.4$ TeV in such models, placing them at the upper right of the allowed region in Figure 3.

Our findings also set a limit on a broader array of new strong interaction physics. Writing eqn.(2.4) in the more conventional form for compositeness studies (2.5) shows that our limit is equivalent to a lower bound $\Lambda_{V8} > 2.4$ TeV on the scale of new color-octet vectorial current-current interactions. Such interactions could arise from quark compositeness or from non-standard gluon interactions (e.g. gluon compositeness) [17].

Finally, we have used the same methods to set a limit on a color-octet axial-vector current-current interaction among quarks. This has the form

$$\mathcal{L}_{eff} = -\frac{4\pi}{2!\Lambda_{A8}^2} J_{5\mu}^a J_5^{\mu a} . \quad (4.1)$$

where $J_{5\mu}^a \equiv \sum_f \bar{q}_f \gamma_\mu \gamma_5 \frac{\lambda^a}{2} q_f$. The contributions of this contact interaction to parton

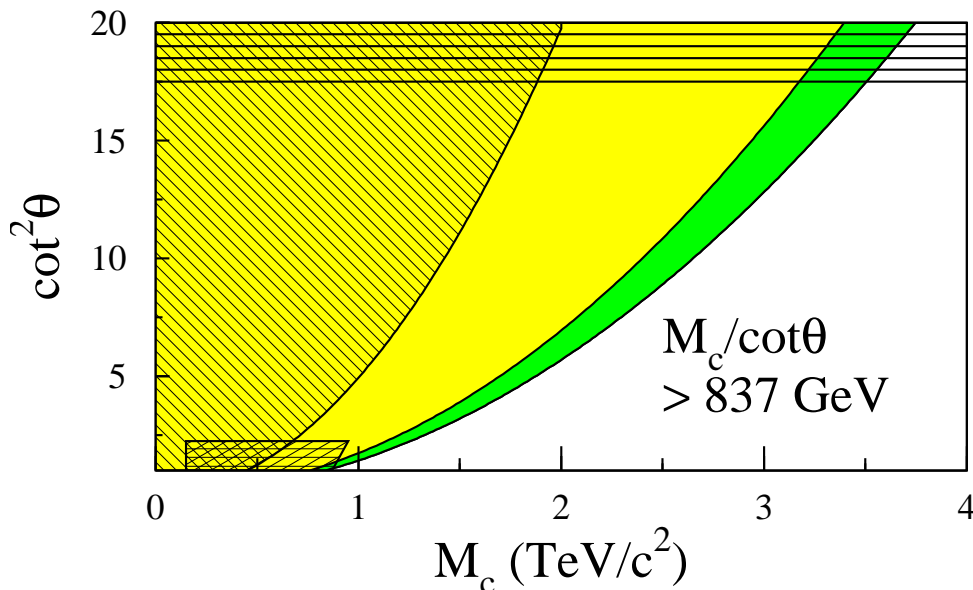


Figure 3: Limits on the coloron parameter space: coloron mass M_c vs. mixing parameter $\cot \theta$. The dark shaded region shows the 95% CL exclusion region for the $D\bar{O}$ measurement of the ratio of cross sections ($M_c / \cot \theta > 837 \text{ GeV}/c^2$). The lightly shaded region shows the area excluded by the $D\bar{O}$ dijet angular distribution [9] ($M_c / \cot \theta > 759 \text{ GeV}/c^2$). The horizontally hatched region at large $\cot \theta$ is not allowed in this phase of the model [1, 8]. The diagonally hatched region is excluded by the value of ρ ($M_c / \cot \theta > 450 \text{ GeV}/c^2$) [1]. The cross-hatched region at low $\cot^2 \theta$ is excluded by the CDF search for new particles decaying to dijets [7].

scattering are given⁴ in [1]. The most conservative bound we find is $\Lambda_{A8} > 2.1 \text{ TeV}$ at 95% CL. Note that we cannot self-consistently interpret this as providing a lower bound on the mass of an axigluon [18, 19] whose exchange underlies the contact interaction (4.1). The relation $\Lambda_{A8} \sqrt{\alpha_s} = M_{\text{axigluon}}$ (since $\cot \theta = 1$ for axigluons) shows that the mass of the supposed axigluon would not satisfy the condition $M_{\text{axigluon}} > \sqrt{\hat{s}}$. Instead, our limit should be interpreted as bounding the scale of contact interactions arising in models of quark compositeness.

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⁴The relevant terms are those in equations (4.2-4.5) in that paper which depend on coefficient c_2 .

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